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The prospects of biolubricants as alternatives in automotive applications

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ABSTRACT

Lubricants perform as anti-friction media. They facilitate smooth operations, maintain reliable machine functions, and reduce the risks of frequent failures. At present, the increasing prices of crude oil, the depletion of crude oil reserves in the world, and global concern in protecting the environment from pollution have renewed interest in developing and using environment-friendly lubricants derived from alternative sources. A biolubricant is renewable lubricants that is biodegradable, non-toxic, and emits net zero greenhouse gas. This study presents the potential of a biolubricant based on vegetable oil as an alternative lubricant according to studies published in highly rated journals in scientific indices. In the first part of this paper, the source, properties, as well as advantages and disadvantages of the biolubricant are discussed. The second part describes the potential of vegetable oil-based biolubricants as alternative lubricants for automobile applications. The final part describes the world biolubricant market and its future prospects. Biolubricants are potential alternative lubricants because of their low toxicity, good lubricating properties, high viscosity index, high ignition temperature, increased equipment service life, high load-carrying abilities, good anti-wear characteristic, excellent coefficient of friction, natural multi-grade properties, low evaporation rates, and low emissions into the atmosphere.

Contents

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1. Introduction

Significant interest is focused on improving environmental friendliness, reliability, durability, and energy efficiency in the automotive and machinery industries. Developing new technological solutions, such as introducing lightweight materials, less harmful fuels, controlled fuel combustion, and more efficient exhaust gas after treatment, are possible means to decrease environmental problems brought by vehicles and machines [1]. High-pressure gases and high temperature expansion resulting from combustion in an internal combustion (IC) engine apply direct force to the components of engine-like pistons, thus moving the components over a certain distance and transforming chemical energy into useful mechanical energy [2]. The reliable and safe operation of an automobile at desired operating conditions requires effective lubrication of moving parts to allow them to slide smoothly over each other. Reducing wear and friction is a key element to decrease energy losses, particularly in engines and drive trains. Mineral oils have been used as a lubricant in IC engines for a long time. However, as a product of the distillation of crude oil, mineral oils can only be used as long as crude oil is available. In addition, disposing of mineral oils leads to pollution in both aquatic and terrestrial ecosystems [3]. Furthermore, the combustion of mineral oils as a lubricant has been proven to emit traces of metals, such as calcium, phosphorous, zinc, magnesium, and iron nanoparticles [4]. Moreover, Tung and McMillan [5] analyzed current and future prospects of mineral oils as lubricants in automobile engines and predicted bleak future prospects. Hence, attempts are made to identify suitable replacements for mineral oils in IC engines.

The increasing oil prices, the depletion of the crude oil reserve in the world, and the demand to protect the environment against pollution caused by lubricating oils and their uncontrolled spillage have renewed interest in developing and using alternative lubricants. Biolubricant oils are perceived as alternatives to mineral oils because they possess certain natural technical properties and they are biodegradable. Compared with mineral oils, vegetable oil-based biolubricants generally exhibit high lubricity, high viscosity index (VI), high flash point, and low evaporative losses [6–12]. Both boundary and hydrodynamic lubrications can be obtained from biolubricants because of their long fatty acid chains and the presence of polar groups in the structure of vegetable oil [13–16]. Vegetable oil can be obtained from oil-containing seeds that are available throughout the world. According to reports, 350 oil-bearing crops are available worldwide. Vegetable oil can both be edible and non-edible. Examples include jatropha [17], karanja, neem, rice bran, rapeseed, castor, linseed, mahua [18], palm [19], sunflower, coconut, soybean, olive, and canola [20]. Many researchers have reported using vegetable oil as engine fuel, but only a few have reported using vegetable oil-based lubricants for automotive applications.

In the last few decades, numerous research papers have discussed the use of biolubricants as alternatives in automotive applications. However, only a few of these papers have analyzed and reviewed biolubricants. The main objective of the present study is to provide information to engineers, policy makers, industrialists, and researchers, who are interested in biolubricants. It presents a comprehensive review of the prospects of using biolubricants as alternative lubricants in automotive applications, including details of vegetable oil properties and their potential as lubricants. Numerous studies published in highly rated journals in scientific indices, including the most recent publications, are reviewed.

2. Overview of lubrication and lubricants

2.1. Lubrication and lubricants

The main purposes of lubrication are (1) to reduce wear and heat loss that result from the contact of surfaces in motion, that is, to reduce the coefficient of friction between two contacting surfaces; (2) to prevent rust and reduce oxidation; (3) to act as an insulator in transformer applications; and (4) to act as a seal against dirt, dust, and water. A lubricant is a substance that reduces friction and wear by providing a protective film between two moving surfaces. Lubrication occurs when two surfaces are separated by a lubricant film. Lubricants are available in liquid, solid, and gaseous forms. A good lubricant exhibits the following characteristics: high VI, high boiling point, thermal stability, low freezing point, corrosion prevention capability, and high resistance to oxidation.

2.2. Classification of lubricants

Lubricants can be classified based on the following criteria. Physical appearance

Solid The film of a solid material is composed of inorganic or organic compounds, such as graphite, molybdenum disulphide, and cadmium disulphide.
Semisolid Liquid is suspended in a solid matrix of thickener and additives, such as grease.
Liquid Examples are oils such as petroleum, vegetable, animal, and synthetic oils.

Base oil resource

Natural oils Oils derived from animal fats and vegetable oils.
Refined oils Oils derived from crude or petroleum reserves, such as paraffinic, naphthenic, and aromatic oils.
Synthetic oils Oils synthesized as end products of reactions that are tailored per requirement; examples are synthetic esters, silicones, and polyalphaolefines.

Applications

Automotive oils Used in the automobile and transportation industry; examples are engine oils, transmission fluids, gear box oils, as well as brake and hydraulic fluids.

Industrial oils Oils used for industrial purposes; examples are machine oils, compressor oils, metal-working fluid, and hydraulic oils.

Special oils Oils used for special purposes according to specific operations; examples are process oils, white oils, and instrumental oils.

2.3. Biolubricants

Biolubricants are made from plants such as palm, soybean, sunflower, rapeseed, and coconut [21]. Biolubricants can also be made from synthetic esters and petroleum oils that satisfy established biodegradability and toxicity criteria. Biolubricants are generally considered as lubricants with high biodegradability as well as low human and environmental toxicity.

2.4. Sources of biolubricants

Producing biolubricants is suitable for alternative energy applications because of their widespread sources. The types of biolubricant feedstock may differ from country to country and highly depend on geographical locations. Biolubricants are made from different crop oils. More than 350 oil-bearing crops are known, among which, only palm, soybean, sunflower, coconut, safflower, rapeseed, cottonseed, and peanut oils are considered as potential alternative biolubricants. Table 1 shows the oil content statistics of some non-edible and edible seeds [21–28]. Palm oil is the main feedstock for biolubricants and biodiesel in Malaysia. Moreover, other non-edible oils such as jatropha, neem, and karanja have received worldwide interest [29].

2.5. Properties of biolubricants

Biolubricants have many valuable and useful physicochemical properties. They offer technical advantages unlike those of typical petroleum-based lubricants. Biolubricants have high lubricity, high VI, high flash point, and low evaporative losses [24,30–33]. Overall, vegetable oil-based biolubricants exhibit several excellent properties compared with mineral oils. Table 2 shows the comparative analysis result of properties of vegetable oils.

2.5.1. Viscosity

Viscosity is the most important property of oil. It indicates resistance to flow, and is directly related to temperature, pressure, and film formation. High viscosity indicates high resistance to flow and low viscosity implies low resistance to flow.

Table 1
Oil content statistics of some non-edible and edible oil seeds [22–29].

Sl. no.	Non-edible species	Oil content (% of volume)	Edible species	Oil content (% of volume)
1	Jatropha	40–60	Rapeseed	38–46
2	Neem	30–50	Palm	30–60b
3	Karanja	30–50	Peanut	45–55
4	Castor	45–60	Olive	45–70
5	Mahua	35–50	Corn	48
6	Linseed	35–45	Coconut	63–65
7	Moringa	20–36	–	–

Table 2
Comparative analysis of properties of vegetable oils.

Properties	Vegetable oils	Mineral oils
Density @20°C (kg/m^3)	940	880
Viscosity index	100…200	100
Shear stability	Good	Good
Pour point, °C	−20…+10	−15
Clod flow behavior	Poor	Good
Miscibility with mineral oils	Good	–
Solubility in water	Not miscible	Not miscible
Oxidation stability	Moderate	Good
Hydrolytic stability	Poor	Good
Sludge forming tendency	Poor	Good
Seal swelling tendency	Slight	Slight

2.5.2. VI

The VI indicates changes in viscosity with changes in temperature. A high VI indicates small changes in temperature, whereas a low VI indicates high changes in temperature. Vegetable oil-based biolubricants have higher VI than mineral oils, which ensures that biolubricants remain effective even at high temperatures by maintaining the thickness of the oil film. Hence, biolubricants are suitable for a wide temperature range.

2.5.3. Pour point

Pour point is the lowest temperature at which oil flows or pours. Pour point is an important factor. Vegetable oil-based biolubricants have lower pour points than mineral oils, thus providing excellent lubrication for cold starts.

2.5.4. Flash point and fire point

Flash point is the lowest temperature at which a lubricant must be heated before it vaporizes. When mixed with air, a lubricant will ignite but will not burn. By contrast, fire point is the temperature at which the combustion of a lubricant continues. Flash and fire points identify lubricant volatility and fire-resistance properties. Both factors are important for transportation and storage requirements. Vegetable oil-based biolubricants have higher flashpoint than mineral oils, thus considerably reducing the risks of fire in case of a lubricant leak, and providing safety on shop floors.

2.5.5. Cloud point

Cloud point is the temperature at which solids dissolve in oil. Wax crystallizes and becomes visible when temperature drops. To prevent clogging of filters, temperature must be maintained above the cloud point.

2.5.6. Acid or neutralization number

The acid or neutralization number indicates the amount of acid or base content required by a lubricant for neutralization.

2.5.7. Oxidation stability

Oxidation stability is the ability to exhibit resistance toward oxide-forming tendency, which increases when temperature rises. The most significant contributors to oxidation include metal surfaces, temperature, contaminants, pressure, agitation, and water. A low oxidative stability indicates that oil oxidizes rapidly during use if it is untreated, becoming thick and polymerizing to a plastic-like consistency.

2.5.8. Rust and corrosion prevention

Rust is chemical reaction between water and ferrous metals; meanwhile, corrosion is a chemical reaction between chemicals and metals. Vegetable oil-based biolubricants are nontoxic and

react less with chemicals, water, and ferrous metals than mineral oils.

2.5.9. Anti-wear properties

Lubricants are satisfactory for low-speed and low-pressure applications. Boundary lubrication occurs when oil viscosity is insufficient to prevent surface contact. Anti-wear additives provide a defensive film at contact surfaces to reduce wear. Anti-wear property is identified by standard laboratory tests. Vegetable oil-based biolubricants have better anti-wear properties than mineral oils.

2.6. Advantages and disadvantages of biolubricants

Vegetable oils can be used as lubricants in their natural form. They have several advantages and disadvantages when considered for industrial and machinery lubrication.

On the positive side, vegetable oils have excellent lubricity, which is far superior compared with that of mineral oils. Vegetable oils also have a high VI. For example, a VI of 223 is common among vegetable oils, whereas a VI of 90–100 is normal for most mineral oils. Another important property of vegetable oils is their high flash points. Typically, the flash point of vegetable oils is 326 °C, whereas that of common mineral oils is 200 °C. More importantly, vegetable oils are biodegradable, generally less toxic, renewable, and reduce dependency on imported petroleum oils. Table 3 summarizes some of the benefits of biolubricants.

On the negative side, vegetable oils in their natural form lack sufficient oxidative stability for lubricant application. Low oxidative stability indicates that oil will oxidize rapidly during use if untreated, becoming thick and polymerizing to a plastic-like consistency. Vegetable oils also have low-temperature limitations, unpleasant smell, poor compatibility with paints and sealants, flushing propensity because of low viscosity, and filter-clogging tendency.

2.7. Applications of biolubricants

Biolubricants provide significant advantages as alternative lubricants for industrial and maintenance applications because of their superior inherent qualities. Biolubricants can be used in sensitive environments and prevent pollution because of their environmental benefits. Biolubricants can be used in various industrial and maintenance applications. Some of their important applications are as follows: industrial oils such as machine oils, compressor oils, metalworking fluids, and hydraulic oils; automotive oils such as engine oils, transmission fluids, gear box oils, as well as brake and hydraulic fluids; and special oils such as process oils, white oils, and instrumental oils. The major benefits of biolubricants shown in Figs. 1 and 2 which shows the areas of biolubricant use in automotive applications [39]. These oils can constructively replace mineral oils as engine oils, hydraulic oils, compressor oils, lubricants for generators, pump sets, tractors, gears, insulating oils, metal working oils, aviation oil, grease, and general or multi-purpose oils.

Table 3
Benefits of bio-lubricants.

Higher lubricity	Lower friction losses, better fuel economy
Lower volatility	Decreased exhaust emissions.
Higher viscosity index	Used for wide temperature range.
Higher boiling temperatures	Less emissions
Higher detergency	Eliminating the requirement of detergent additives.
Higher flashpoints	Higher safety on shop floor
Rapid biodegradation	Reduced toxicological and environmental hazards.
Oil mist and oil vapor reduction	Leads to less breathing of oil mist into the lungs.
Better skin compatibility	High cleanliness and less dermatological at work place

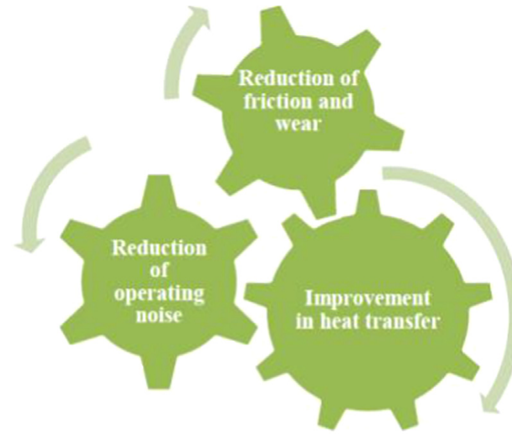

Fig. 1. Major benefits achieved used for industrial purpose from bio-lubricants.

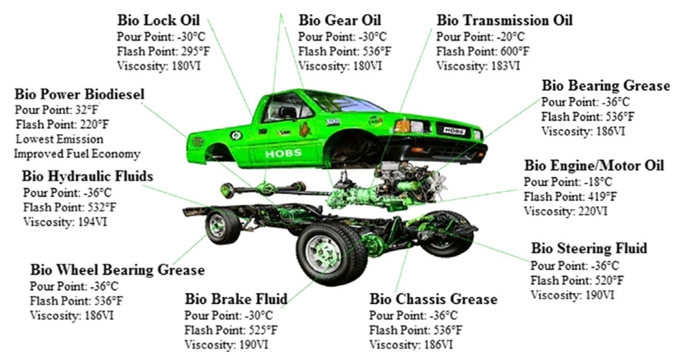

Fig. 2. Lubrication requirements for a pick-up truck [39].

Table 4
Bio-degradability of some base fluids.

Types of fluids	Biodegradability (%)
Mineral oils	20–40
Vegetable oils	90–98
Esters	75–100
Polyols	70–100
Trimelliates	0–70

2.8. Biodegradation of biolubricants

Biodegradability is the capability of a material to be decayed by microorganisms [40]. A lubricant is classified as biodegradable if its percentage of degradation in a standard test exceeds a certain marked level. Vegetable oils exhibit better biodegradability than mineral oils and others, as shown in Table 4. The ecotoxic property of lubricating materials depends on the base oils and additives used in their production [41]. Biodegradability is primarily influenced by the base oil of lubricants [42,43]. It depends on the chemical structures of organic compounds. The chemical composition of base oils changes during the application of lubricants, that is, when they are introduced to factors such as air, temperature, metals, humidity, and pressure. The property changes of chemical

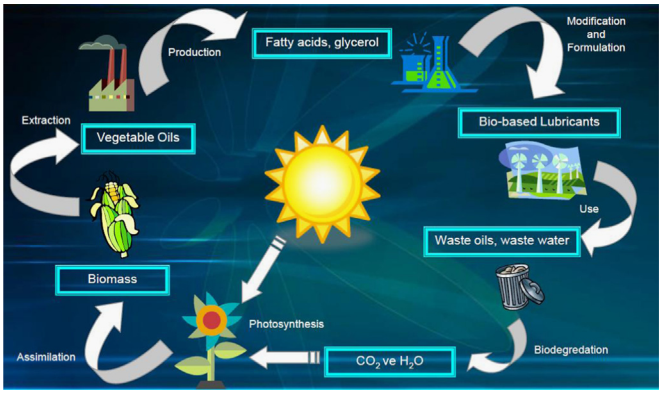

Fig. 3. Life cycle of bio-based lubricants.

Table 5
Physio-chemical properties of non-edible oils [24,30–38].

Vegetable oils non-edible	Density (Kg/m^3)	Kinematic viscosity at 40 °C (mm^2/s)	Oxidation stability 110°C, h	Cloud point °C	Flash point °C
Jatropha	878	4.82	2.3	2.75	136
Karanja	918	4.80	6.0	9.0	150
Mahua	850	3.40	–	–	210
Neem	885	5.20	7.2	14.5	44
Castor	898	15.25	1.2	−13.5	260
Tobacco	887	4.25	0.8	–	166

structures during service are responsible for biodegradability [41]. Fig. 3 shows the life cycle of biolubricants.

3. Biolubricants as alternative lubricants

Biolubricants have numerous valuable and useful physico-chemical properties, and offer several technical advantages. Biolubricants have high lubricity, high VI, high flash point, and low evaporative losses [24,30–38]. Tables 5 and 6 show the physio-chemical properties of biolubricants based on several non-edible and edible oils [24,30–38]. Various biolubricant-related research and development projects have been completed to improve physicochemical properties. These studies have found that biolubricants can be efficient and inexpensive substitutes to petroleum-based oils. The summary of the research on vegetable oil-based biolubricants conducted by various researchers is shown in Table 7. Moreover, researchers have reported that biolubricants provide better lubricity than petroleum-based oils [8]. As a result, biolubricants are becoming more popular because of these positive characteristics. The major aspects include corrosive nature [44–46] and the reactivity of unsaturated hydrocarbon chains [47–49]. The wear properties of biolubricants have been studied by several researchers using different Tribometer techniques. Sulek et al. [48] investigated the tribological properties of rapeseed biolubricants and found that they exhibit a lower friction of coefficient than petroleum-based oils. The development of the lubricity of biolubricants was reported for each low blend levels [49]. A research found that friction and wear have been slightly improved with the increase in temperature [8]. Kalam et al. [50] experimentally investigated the friction and wear characteristics of a normal lubricant, that is, an additive-added lubricant and waste vegetable oil (WVO)-contaminated lubricants. The WVO-contaminated lubricants with amine phosphate as anti-wear additive reduced wear and friction coefficient and increased viscosity; thus, waste palm oil with a normal lubricant and amine

Table 6
Physio-chemical properties of edible oils [24,30–38].

Vegetable oils edible	Density (Kg/m^3)	Kinematic viscosity at 40 °C (mm^2/s)	Oxidation stability 110 °C, h	Cloud point °C	Flash point °C
Palm	875	5.72	4.0	13.0	165
Sunflower	878	4.45	0.9	3.42	185
Coconut	805	2.75	35.4	0	112
Soybean	885	4.05	2.1	1.0	176
Linseed	890	3.74	0.2	−3.8	178
Olive	892	4.52	3.4	–	179
Peanut	882	4.92	2.1	5.0	177
Rape seed	880	4.45	7.5	−3.3	62
Rice bran	886	4.95	0.5	0.3	–

phosphate additive could be used as a lubricant substitute (maximum 4%).

Maleque et al. [51] investigated the tribological performance of palm oil methyl ester blended lubricant in a steel cast iron pair and found that corrosive wear and pits on the damaged surface are the most common wear modes. Another study [52] observed that more than 5% of palm oil methyl ester in a lubricant caused oxidation and corrosion. This study also reported that the lubrication properties of biolubricants are influenced by temperature, oxidation, and moisture absorption. Mineral oils are mostly used as engine oil, hydraulic oil, metal working fluid, insulating oil, and grease. Products from vegetable oils such as jatropha, neem, karanja, soybean, palm, coconut, castor, olive, mahua, and sunflower exhibit better or at least, similar performances as petroleum or synthetic oil-based products, aside from being less expensive [53–56]. Asadauskas et al. [57] investigated the lubrication properties, such as viscosity, oxidative, deposit formation, and lubricity, of biodegradable lubricants. Their experiment results showed that the VI of vegetable oils is greater than those of mineral oils. Vegetable oils are preferred over synthetic fluids because they are from renewable sources, less expensive, and eco-friendly [58]. Furthermore, vegetable oil-based lubricants are biodegradable and non-toxic, unlike conventional mineral-based oils [59]. Vegetable oils have low volatility because of the high molecular weight of the triacylglycerol molecule. They also have a narrow range of viscosity changes with temperature. Vegetable oils are regarded as alternatives to mineral oils as lubricants because they possess certain inherent technical properties and because of their biodegradability. Compared with mineral oils, vegetable oils have a high flash point, high VI, high lubricity, and low evaporative loss [60]. Zulkifli et al. [61] investigated the wear prevention characteristics of a palm oil-based Trimethylolpropane (TMP) ester as an engine lubricant in a four-ball machine for different lubrication regimes, namely, hydrodynamic, elastic hydrodynamic, and boundary lubrications. The blended lubricants consisted of 5%, 10%, 15%, 20%, and 100% palm oil TMP esters with ordinary lubricant. The results showed that the palm oil-based TMP ester-based lubricant improves wear-preventive lubrication properties in terms of the coefficient of friction and the wear-scar diameter. Arumugam et al. [62] investigated the effect of biolubricants and biodiesel-contaminated lubrication on the tribological behavior of a cylinder liner piston ring combination by using a pin-on-disc Tribometer. The discs were prepared by white cast iron alloyed from an actual engine cylinder liner material by casting. Similarly, pins were prepared by white cast iron alloyed from an actual top compression ring material. Four different lubrication oil samples, that is, 10% biolubricants, 10% B20R with SAE 20W40 commercial lubricant, 10% diesel with SAE 20W40 commercial lubricant, and SAE 20W40 commercial lubricant, were prepared for the analysis. The biolubricant reduced the coefficient of friction as well as frictional force and wear. Moreover, the

Table 7
Summary of the work done by various researchers on vegetable oil based bio-lubricant.

Bio-lubricants	Reference lubricant	Test method and condition	Result	Reference
Coconut oil	SAE 20W50	Four-ball tester	Less coefficient of friction Higher anti-wear properties Better lubricity Properties	[8]
Palm oil	SAE20W50	High frequency reciprocating rig (Ball-on-Flat). steel–steel pair contacts.	Less corrosive nature Lower coefficient of friction Good oxidation and anti-corrosion properties Reactivity of unsaturated hydrocarbon chains Strong stability of the lubricant film	[44–49,51,52]
Waste palm oil	SAE 40	Four-ball tribo-tester, with standard test method Ip-239	Lower coefficient of friction Higher viscosity	[50]
Vegetable oils (Jatropha, Neem, Karanja, Soybean, Palm, Coconut, Castor, Olive, Mahua, Sunflower, etc.)	Petroleum based mineral oils	Different tribo-tester with standard test method	High flash point High viscosity index High lubricity Low evaporative loss Offer better performance Less expensive Cheaper and eco-friendly	[53–56,60,66,67,70,71]
Castor oil	Super refined mineral oil	Four-ball wear tester	Greater viscosity index Lower deposit forming tendencies Lower volatility Higher concentrations of antioxidants	[57]
Soybean oil	Petroleum based mineral oils	Four-ball tribo-tester	Less coefficient of friction Better lubricity properties Non-toxic Cheaper and eco-friendly	[58,59]
Palm oil based TMP ester	SAE 40	High frequency reciprocating machine	Good wear prevention properties in terms of coefficient of friction and wear scar diameter	[61]
Castor oil and palm oil	SAE 20W40	Pin on disc tribo wear tribometer	Reduced the coefficient of friction frictional force and wear Excellent lubricity properties Renewable and biodegradable Eco-friendly Possess lower volatility	[62,63]
Pongamia oil	SAE 20W40	Four-stroke, single cylinder, water cooled, direct-injection diesel CI engine	Minimum BSEC and highest BTE at medium and high load conditions Lesser frictional losses Improve the efficiency Completely eliminate emission	[64]
Jatropha oil	SAE 20W40	Pin on disc machine	Lower Wear Loss Lower cumulative weight loss Lower friction coefficient	[65]
Chemically modified rapeseed oil bio-lubricant	SAE20W40	High frequency reciprocating tribometer test rig	Good oxidative stability Improved Cold Flow Property Better performance in terms of frictional force and co-efficient of friction	[68]
Soybean oil	Commercial synthetic lubricant	High frequency reciprocating tribometer test rig	Extremely large viscosity	[69]

biolubricants exhibited better lubricity than the other test samples under similar operating conditions. The long-chain fatty acid in palm oil produced a hydrocarbon layer that protected surfaces from wear, thus increasing the wear resistance of biolubricants [63]. In addition, physical observation on the wear surfaces found that the biolubricant and biodiesel-contaminated lube oil provide smoother surfaces than the diesel-contaminated lube oil. The aforementioned research concluded that engine lubricants formulated from vegetable oils are renewable, eco-friendly, biodegradable, and exhibit low volatility.

Bekal et al. [64] conducted an experimental investigation on a biolubricant (Pongamia oil) as an alternative to mineral oil for an IC engine. In their analysis, neat Pongamia oil, a blend of Pongamia oil with mineral oil, and neat mineral oil were used as lubricants and tested on a commercial four-stroke, single-cylinder, water-cooled, direct-injection diesel engine. Using neat Pongamia oil as a lubricant provided the minimum brake specific energy consumption and the highest brake thermal efficiency at medium- and high-load conditions because of the low viscosity of Pongamia oil lubricant. Thus, frictional losses were less, and the high efficiency of all fuel variants and Pongamia oil improved efficiency and completely eliminated the emission of metal traces unlike in mineral oil lubricants. Bhale et al. [65] simulated the wear characteristics of a cylinder liner ring with diesel and biodiesel by a pin-on-disc machine. The discs were made from an actual engine cylinder liner. Pins were made from the top piston ring and used lube oil contaminated with Jatropha oil methyl ester and diesel. The lube oil contaminated with Jatropha oil exhibited lower wear, cumulative weight loss, and friction coefficient than the diesel-contaminated lube oil under similar operating conditions because of the presence of oxygenated moieties in Jatropha oil methyl ester, which, along with double bonds, led to additional improvement in overall lubricity.

Suhane et al. [66] studied the potential of non-edible vegetable oils as alternative lubricants for automotive applications and concluded that lubricants based on such oils are renewable and biodegradable in nature and do not interfere with the food

consumption demands of the country. The environmental compatibility of vegetable oils provides them with an advantage over conventional mineral oils in terms of overall operating costs. Lubricants based on vegetable oils still comprise a narrow segment of the market. Nonetheless, vegetable oils have more valuable and useful physicochemical properties than mineral oils and offer more technical advantages than usual petroleum-based lubricants. For example, vegetable oils have a high flash point, high VI, high lubricity, and low evaporative losses. Jain et al. [67] studied the capability of biolubricants as alternative lubricants for industrial and maintenance applications and concluded that biolubricants can be used in various industrial and maintenance applications such as hydraulic fluids, metal working fluids, grease, and two-stroke engine oil. Biolubricants exhibit low toxicity, good lubricating properties, high VI, high ignition temperature, increased equipment service life, high load-carrying abilities, good anti-wear characteristic, excellent coefficient of friction, natural multi-grade properties, low evaporation rates, low emissions into the atmosphere, and rapid biodegradability. Using biolubricants in industrial and maintenance applications reduces cost and increases competitiveness. Moreover, reducing the use of petroleum-based lubricants in industrial and maintenance applications become possible by using biolubricants.

Arumugam et al. [68] experimentally investigated the tribological characteristics of a diesel engine cylinder liner and piston ring combination under chemically modified biolubricants and commercial synthetic lubricant by using a high-frequency reciprocating Tribometer test rig. The chemically modified biolubricants exhibited good oxidative stability, improved cold flow property, and better performance in terms of frictional force and coefficient of friction than the commercial synthetic lubricant. The coefficient of friction of the chemically modified biolubricants was 23% less than the commercial synthetic lubricant because of the formation of a stable polymeric film on the metal surface during boundary lubrication. Approximately 12% more wear was observed with the chemically modified biolubricant than with the commercial synthetic lubricant because of the anti-wear additives in the latter. Ting et al. [69] analyzed the viscosity and working efficiency of soybean oil-based biolubricants to develop engine biolubricants. This previous work used mixtures of original soybean oil, epoxidized soybean oil, and hydrogenated soybean oil as base oils. The result showed that the epoxidized soybean oil has a significantly larger viscosity than the engine lubricants and the original soybean oil, whereas the hydrogenated soybean oil clearly presents the opposite results. Viscosity analysis provides efficient formations to fit the viscosity of engine lubricants by mixing the three soybean oils as base oils. Chauhan et al. [70] studied vegetable oils as renewable raw materials for new industrial lubricants and found that vegetable oils with high oleic contents are the best alternatives to conventional mineral oil-based lubricating oils and synthetic esters. Vegetable oils are preferred over synthetic oils because they are more eco-friendly, are from renewable resources, and are less expensive. Nagendramma et al. [71] studied the development of eco-friendly/biodegradable lubricants and found that synthetic and vegetable oil-based esters offer the best choices in formulating environment-friendly lubricants for automotive transmission fluids, metal working fluids, cold rolling oils, fire-resistant hydraulic fluids, industrial gear oils, neat cutting oils, and automotive gear lubricants either alone or in combination. Moreover, the shift toward biodegradable products is increasing rapidly. Eco-friendly/biodegradable lubricants have been predicted to have a worldwide volume share of approximately 15% and a volume share in some regions of up to 30% in the next 10 years to 15 years. The world lubricant market will face numerous changes within the next 5 years to 10 years, and it will certainly remain an interesting field.

4. Current status of the lubricant market

4.1. Global lubricant market

During the past 10 years, the global lubricant market has undergone dramatic changes. Worldwide demand for lubricants has remained at approximately 35 million tons per year since 1991. An estimated 37.4 million tons of lubricants were consumed worldwide in 2004, with 53% being automobile lubricants, 32% being industrial lubricants, 10% being process oils, and 5% being marine oils [72]. In 2005, 37.9 million tons of lubricants were used worldwide, with the Asia-Pacific region overtaking North America since 2004. A 2007 Freedonia report stated that 41.8 million tons of lubricants were consumed in 2007, and the overall growth rate was 0.8%. Limited data are available in the market for 2008. However, the annual growth rate is expected to reach approximately 2% starting in 2012. The fastest growth will occur in the Asia-Pacific, with China being the major gainer. Figs. 4 and 5 present the lubricant world market and the segmentation by region and application area, respectively. Tables 8 and 9 show the forecast growth in lubricant demand by region and application area, respectively, from 2005 to 2015.

4.2. International status

The world has approximately 1700 small and large lubricant manufacturers. An estimated 300 of these manufacturers are

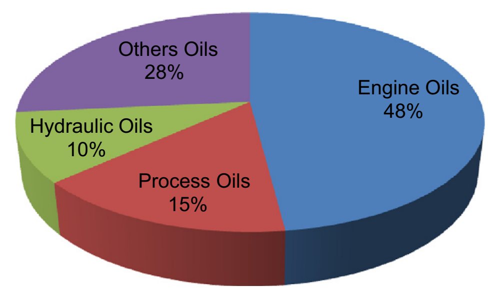

Fig. 4. World market, the segmentation by application area.

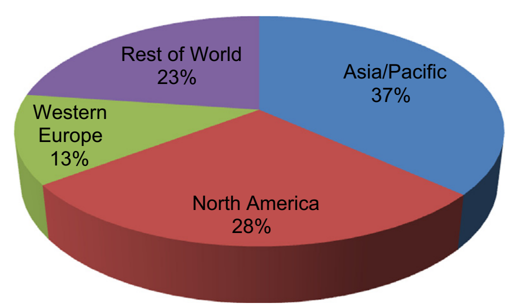

Fig. 5. World market, the segmentation by geographical.

Table 8
Forecast lubricants demand growth by region, 2005–2015.

Region	Growth rate, %
Western Europe	−3.3
North America	0.4
Near & Middle East & Africa	1.2
Central & Eastern Europe	1.5
Central & South America	1.9
Asia Pacific	3.5

Table 9
Forecast lubricants demand growth by region based on application area, 2005–2015.

Region	Consumer automobile, %	Commercial automobile, %	Industrial, %
USA	0.25	0.50	0.50
China	10	6.50	7
Russia	4	3	3
Japan	1	−2	−1.75
India	4	3.5	3
Germany	−3	−4	−2
Canada	1	2	1
Brazil	3	3.5	3.5
UK	−2.25	−2.1	−2
France	−1.75	−2	−1

Table 10
Global top 10 lubricant manufacturers.

Manufacturers	Product name	Country
Shell	Shell	Great Britain/The Netherlands
Exxon Mobil	Exxon Mobil	USA
BP	BP	UK
Chevron	Chevron	USA
Petro China	Petro China	China
Lukoil	Lukoil	Russia
Fuchs	Fuchs	Germany
Nippon oil	Nippon oil	Japan
Valvoline	Valvoline	USA
Conoco Phillips	Conoco Phillips	USA

located in Europe. These manufacturers are mainly vertically integrated petroleum companies, the main business of which is to discover, extract, and refine crude oil. The 1200 independent lubricant companies focus on engine, gear, and hydraulic oils. Less than 2% of lubricant manufacturers produce more than 60% of the global volume of lubricants [73]. Table 10 shows the top 10 lubricant manufacturers in the world.

4.3. Malaysia status

In Malaysia, research on biolubricants is becoming a top priority as environment friendly lubricants have become commercially available. Vegetable oils are promising candidates for biodegradable biolubricants. The Malaysian government motivates private companies to establish more treatment plants and to upgrade biolubricants for automotive and industrial uses. The increase in lubricant demand in Malaysia will be aided by the ongoing expansion of rebound in manufacturing and other industrial activities because of the ongoing rapid industrialization and the increasing vehicle ownership rates. The Malaysian Automotive Association forecast that motor vehicles will recover from the slight decrease in 2009. Table 11 presents strong growth until 2014 [74,75].

4.4. Currently available commercial products

The most up-to-date literature report on biolubricants shows that a number of manufacturers currently market environmentally acceptable biodegradable biolubricants in the United States, Europe, and Asia. US patent numbers 6,278,006 August 21, 2001 [76], 6,420,322 July 16, 2002 [77], 20050150006 July 7, 2005 [78], US 6,943,262 September 13, 2005 [79], US 20080293602 November 27, 2008 [80], and US 20100196424, August 5, 2010 [81] revealed numerous works related to biolubricants. Moreover, some products from soybean oils are presently available, including those

Table 11
Malaysian Automotive Association (MAA) forecast of vehicle sales.

Year	Passenger vehicles	Commercial vehicles	Growth rate, %
2009	486,342	50,563	2.0
2010	498,300	51,700	2.4
2011	514,500	52,000	3.0
2012	530,500	53,000	3.0
2013[a]	546,000	54,000	2.8
2014[a]	562,400	55,600	3.0

[a] Forecast.

with applications in automotive, rail curve track, machinery, and food grade. The development of more than 30 viable soybean-based lubricants, grease, and metal working fluid formulations includes high-performance multi-grade hydraulic fluid [82]. In the global market, biolubricants are becoming increasingly successful in displacing mineral oil products in engine oils, process oils, transformer fluids, compressor oils, turbine oils, elevator and other hydraulic fluids, and metal rolling oils.

5. Future prospects

The increase in world lubricant demand will be aided by the current expansion of the rebound in manufacturing and other industrial activities because of the ongoing rapid industrialization and the increasing vehicle ownership rates, particularly in China. These trends will also favor growth in Africa, the Middle East, and Latin America. The fastest growth in lubricant demand in 2013 is reported in the manufacturing sector and in other markets. The Asia-Pacific region, led by China, will remain as the primary driver of growth in these markets because companies worldwide will continue taking advantage of the relatively low labor costs and the political stability in the region, which are key advantages [83,84].

During the 1950s, the most important requirements for base oils were appropriate viscosity and the absence of acidic components. During the 1960s, base oils were downgraded into solvents or carriers for additives. During the 1970s, several synthetic fluids with a uniform and basic chemical structure exhibited superior performance compared with those of mineral base oils. During the 1980s, low-priced, quasi-synthetic hydro-cracked oils were introduced in Western Europe; these oils had properties that closely matched those of synthetic hydrocarbons. During the 1990s, base oil development was influenced by the demands on lubricant performance, as well as by environmental, health, and safety criteria. This phenomenon led to more chemically pure oils, and their oleo chemical derivatives experienced a renaissance because of their rapid biodegradability. The trend toward increasing performance and improved compatibility continued during the first decade of the new millennium [85]. The current quality trends in lubricants indicate a significant shift toward viscosity grades and product specifications.

In fact, biolubricants exceed the performance of mineral lubricants in terms of viscosity, low carbon-forming tendency, stability, oxidation stability, volatility requirement, and response to additives. Providing better performing lubricants for specific applications is a challenge in the lubricant industry [86]. Developing new-generation heavy-duty lubricants is an example of the response of the industry to the demand for lubricated automotive equipment that will reduce environmental loading by decreasing emissions and to achieve biodegradability and non-toxicity [87]. Biolubricants are now widely accepted as offering a number of inherent performance advantages over conventional petroleum-based oils to formulate modern automotive engine oils.

6. Conclusions

Vegetable oil-based biolubricants are renewable and biodegradable. The biodegradability of biolubricants is their strongest point in case of automobile applications. In response to increasing concern on environmental impacts, automobile fuels and lubricants offer the most plausible solution to obtaining renewable and eco-friendly lubricants. The environmental compatibility of vegetable oils provides them with an advantage over conventional mineral oils in terms of overall operating costs. However, vegetable oil-based biolubricants still comprise a narrow segment of the market. The use of lubricants in open applications such as two-stroke engines, chain saws, and forestry, is slowly but steadily increasing because of the concern on environmental safety and the restrictions on environmental regulations. Such applications can have direct exposure to soil and water bodies when eco-friendly lubricants are used.

Biolubricants are potential alternative lubricants for automobile applications. The advantages of using biolubricants include low toxicity, good lubricating properties, high VI, high ignition temperature, increased equipment service life, high load-carrying abilities, good anti-wear characteristic, excellent coefficient of friction, natural multi-grade properties, low evaporation rates, low emissions into the atmosphere, and rapid biodegradability. Improvements are inevitable and are already being recorded with an increasing number of studies directed toward such areas. Although a number of studies are already available in this field, further systematic research that confirms the tribological behavior of different biolubricant blends must be conducted. The present study can support the establishment of biolubricants, as well as encourage and support research on using renewable natural sources as alternatives.

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